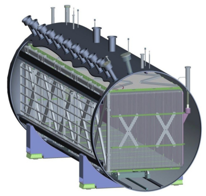


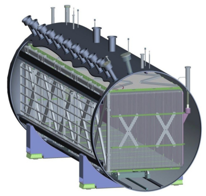
Space Charge Effects at MicroBooNE

Michael Mooney (BNL)

On behalf of the MicroBooNE Collaboration

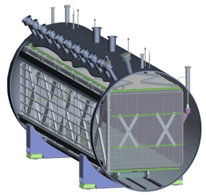
DPF 2015, Ann Arbor, MI

August 4th, 2015

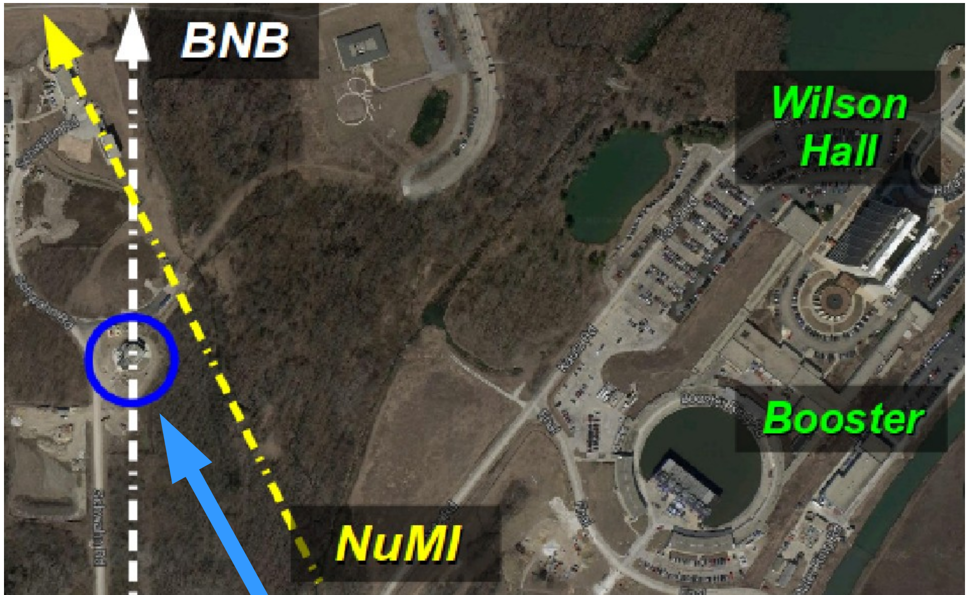


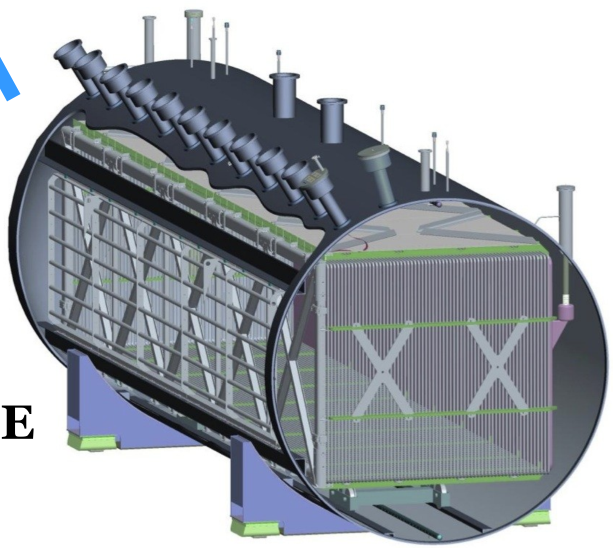
Outline

- **MicroBooNE and LArTPC Technology**
- Space Charge Effect (SCE) in LArTPC's
- Calibration of SCE and First Results with Toy MC



MicroBooNE



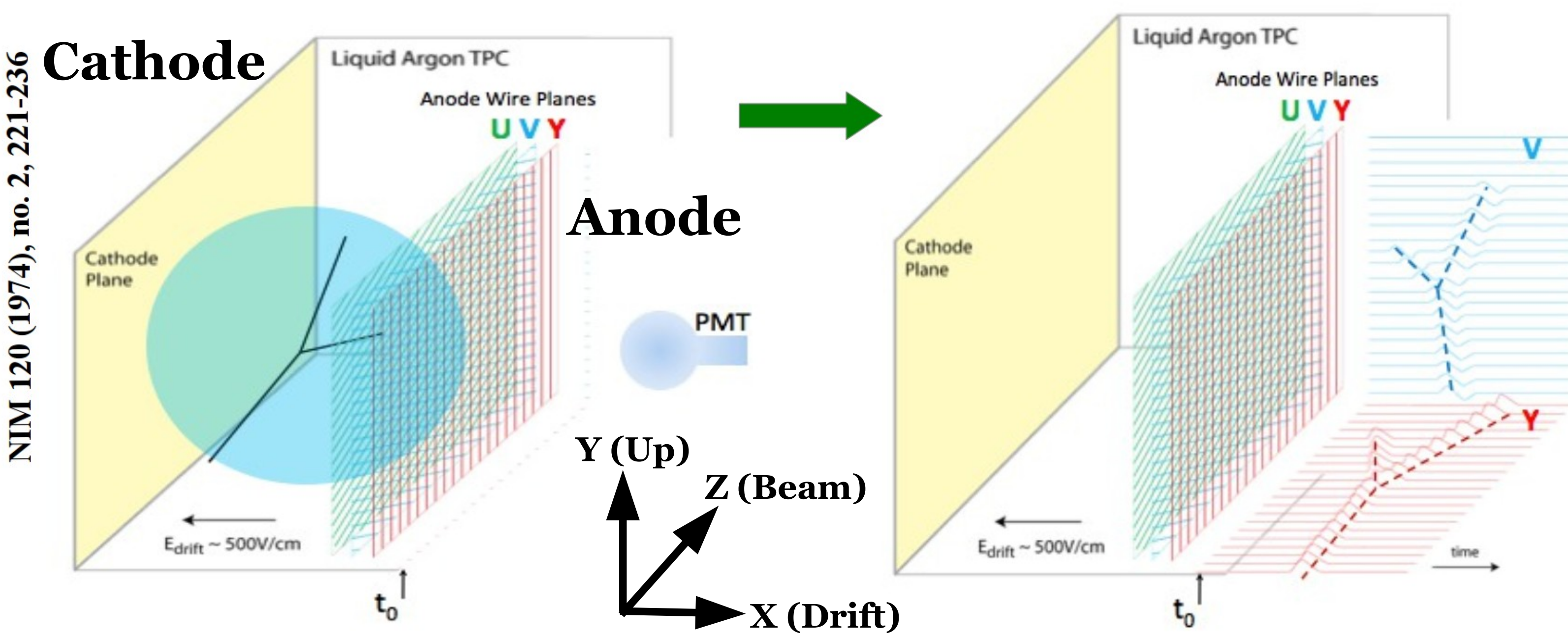


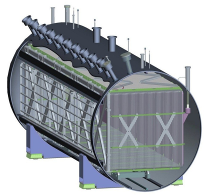
MicroBooNE Cryostat

- **MicroBooNE** ("Micro Booster Neutrino Experiment"): LArTPC (Liquid Argon Time Projection Chamber) at Fermilab
  - 170-ton total mass (**80-ton active mass**), 470 m baseline
  - Receives Booster Neutrino Beam (BNB) and Main Injector neutrino beam (NuMI) – $\overline{\nu}_\mu/\nu_\mu$ sources
  - TPC: **10.3** m long, **2.3** m tall, **2.5** m wide
  - Ionization signals collected via three anode wire planes (8000+ channels)
  - PMT system for light collection
  - <u>Chief physics goal</u>: confirm or rule out sterile neutrino hypothesis from LSND and MiniBooNE low energy $\overline{\nu}_e/\nu_e$ excesses

LArTPC Technology

♦ Reconstruction of neutrino-Ar interaction events with LArTPC
  - 8000+ readout channels via three wire planes at anode
  - Two **induction** planes ("U" and "V") and one **collection** plane ("Y")
  - Provides millimeter-scale resolution and sub-microsecond-scale timing
  - **Combine information** from three planes to reconstruct particles in **3D**
  - **Assumes uniform drift E field (500 V/cm) for reconstructing drift coordinate ("X") of ionization electron signals**





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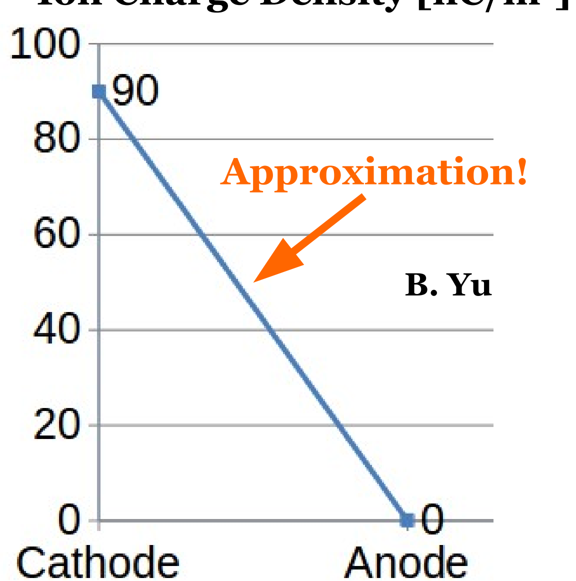
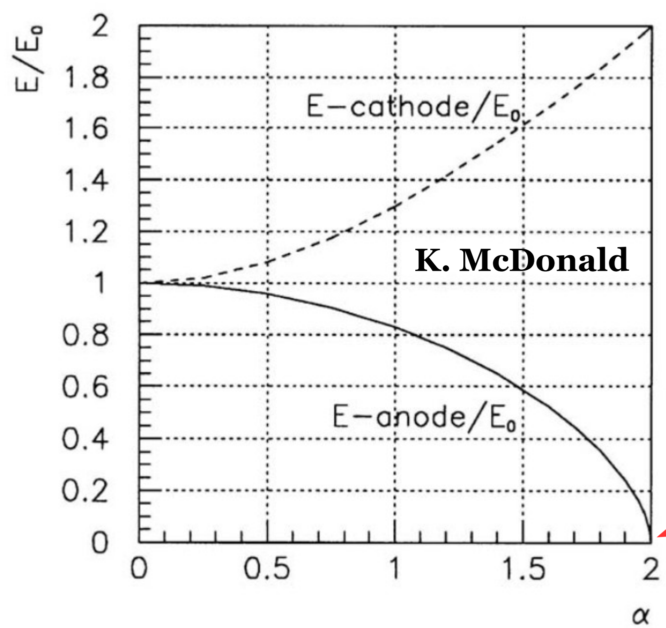
Space Charge Effect

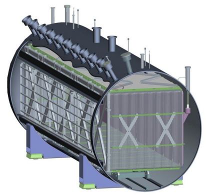
- **Space charge**: excess electric **charge** (slow-moving argon ions) distributed over region of **space** due to ionizing cosmic muons passing through the liquid argon
  - Modifies E field in TPC, thus track/shower reconstruction
  - Affects LAr neutrino experiments on surface, such as **MicroBooNE**
    - Magnitude of distortion scales with **D³**, **E$^{-1.7}$**





$$\alpha = \frac{D}{E_0}\sqrt{\frac{K}{\epsilon\mu}}$$

$$\mathbf{v} = \mu\mathbf{E}$$



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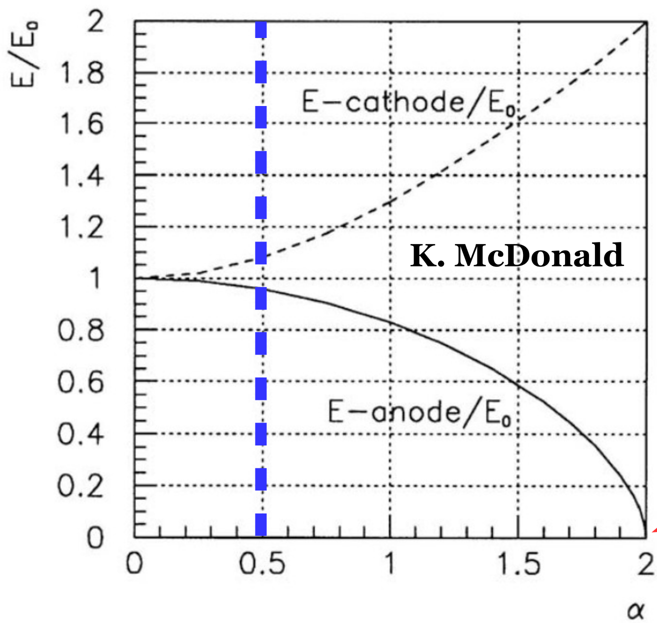
  - Affects LAr neutrino experiments on surface, such as **MicroBooNE**
    - Magnitude of distortion scales with $\mathbf{D^3}$, $\mathbf{E^{-1.7}}$

MicroBooNE:

D = 2.56 m

E = 500 V/cm

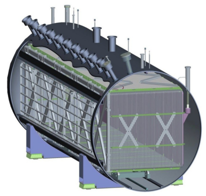
$\mathbf{K = 2 \cdot 10^{-10}\ C/m^3/s}$



$$\alpha = \frac{D}{E_0}\sqrt{\frac{K}{\epsilon\mu}}$$

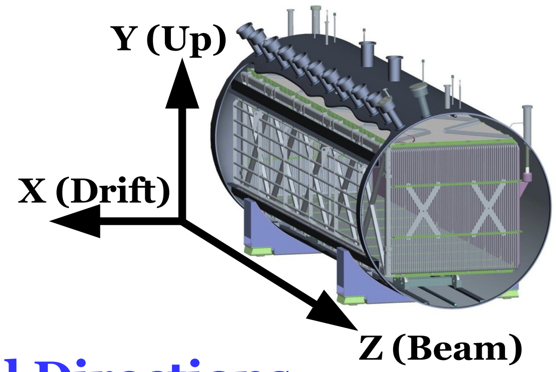
$$\mathbf{v} = \mu\mathbf{E}$$

No Drift!

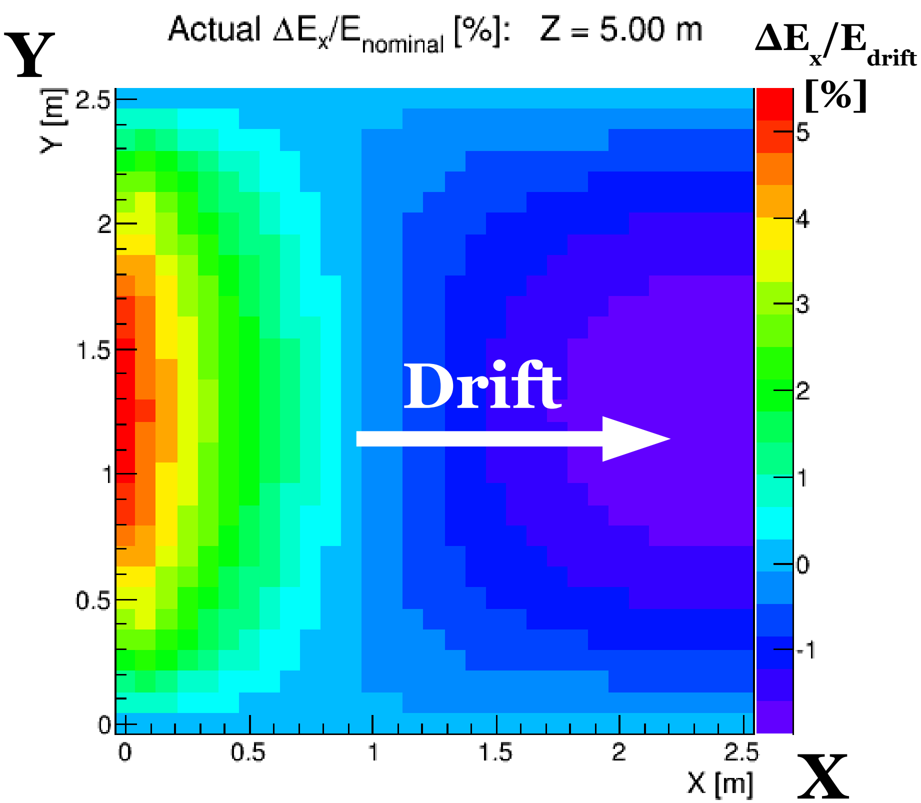


Impact on E Field

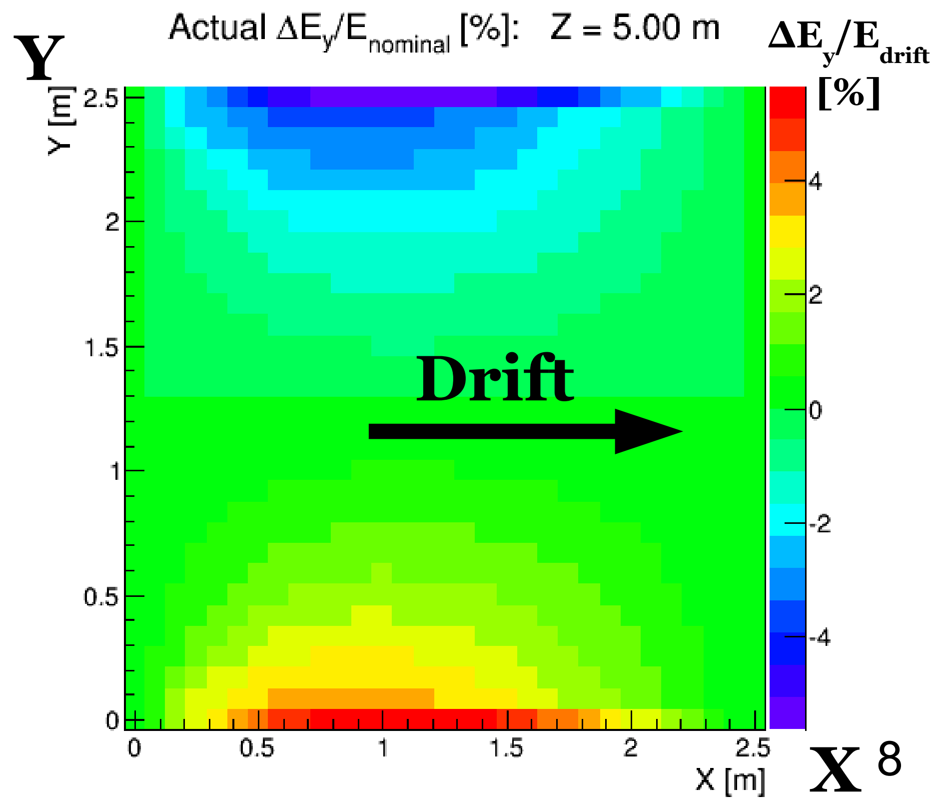
- Visualization of E field in central Z slice
  - Charge deposition rate same throughout TPC
  - No liquid argon flow



Drift Direction

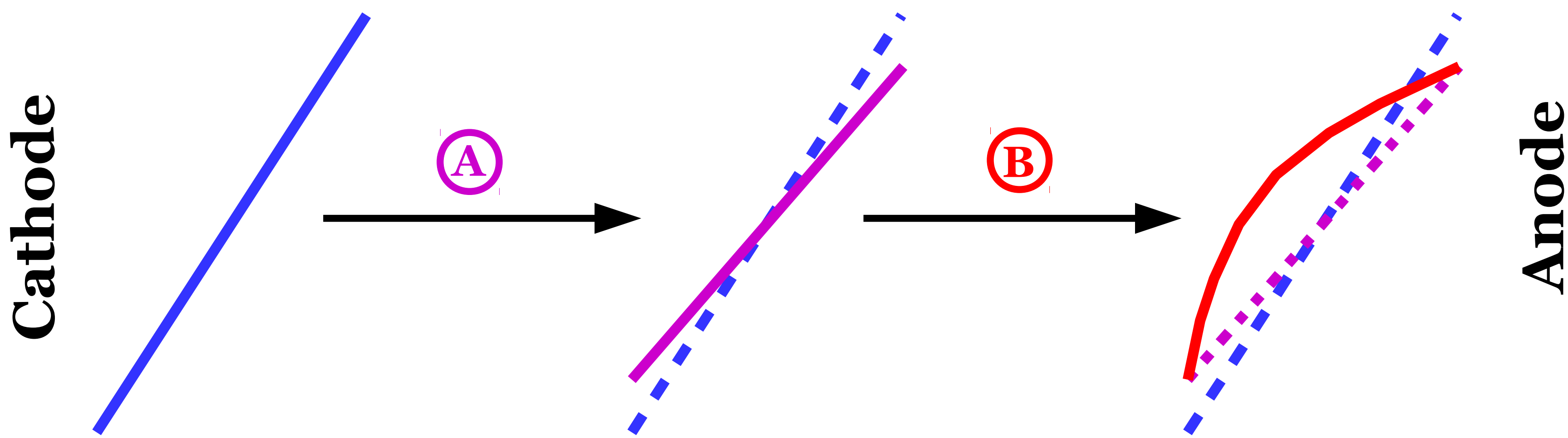


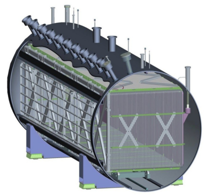
Lateral Directions



Impact on Track Reco.

- Two distinct effects on reconstructed **tracks**:
  - A • Reconstructed track shortens laterally (looks rotated)
  - B • Reconstructed track bows toward cathode (greater effect near center of detector)
- Can obtain straight track (or multiple-scattering track) by applying corrections derived from data-driven calibration





Sample "Cosmic Event"

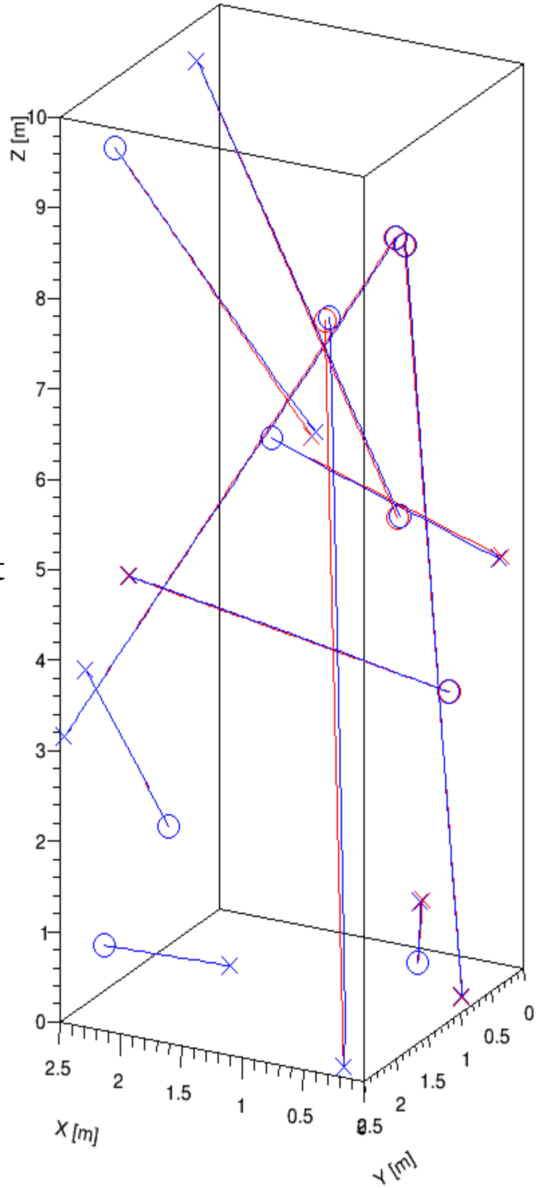
Without SCE

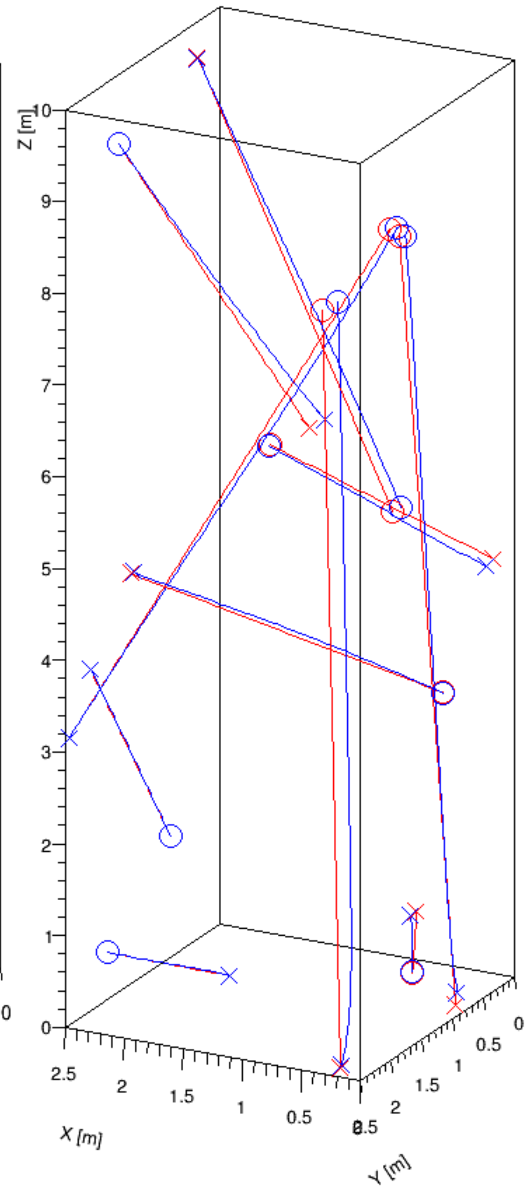
vs.

With SCE

Nominal Drift Field

500 V/cm



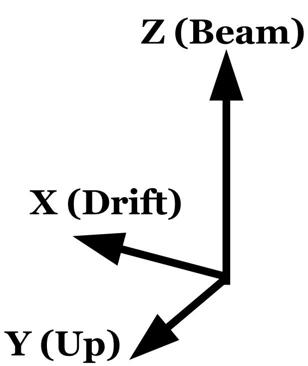


Simulation:

1. **Fourier Series** solution to BVP for E field on 3D grid
2. **Interpolation** between grid points
3. **Ray-tracing** to obtain distortions

Half Drift Field

250 V/cm



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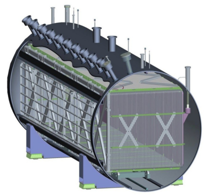
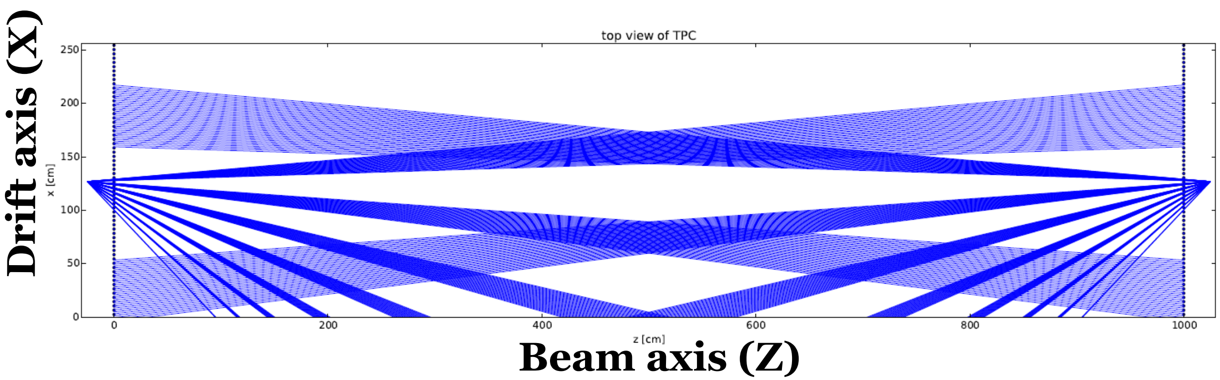
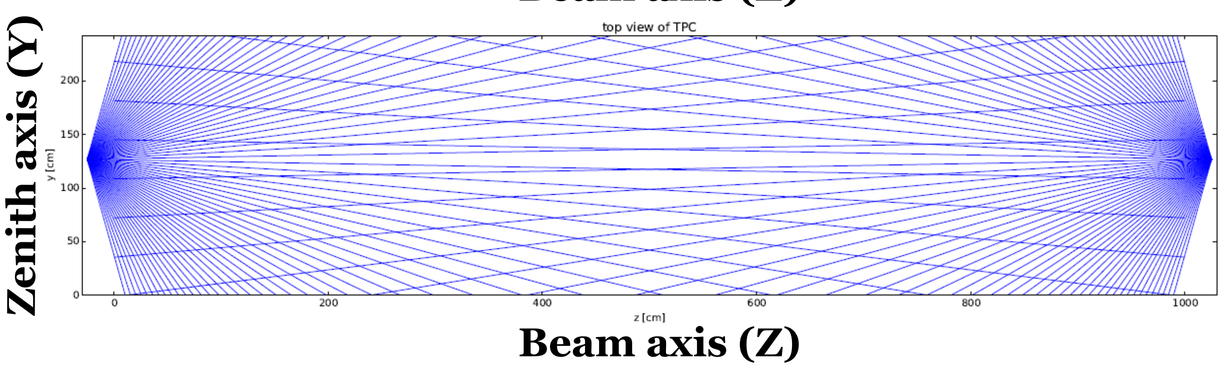
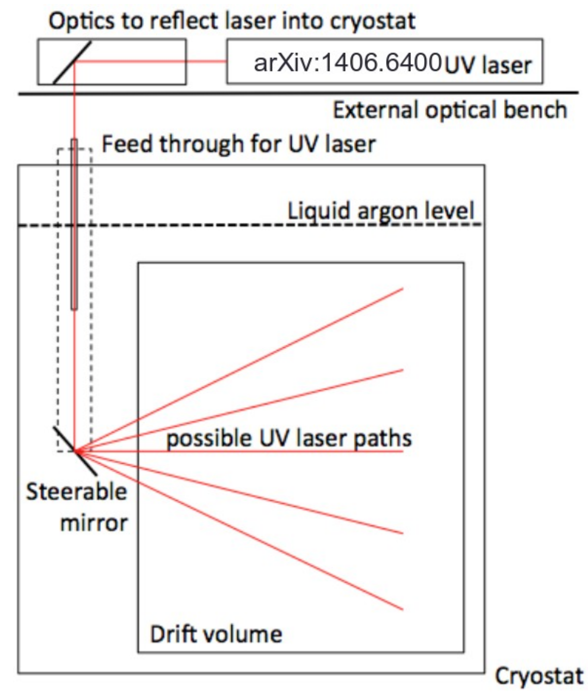


UV Laser System

- UV laser system installed at each end (in beam direction) of MicroBooNE TPC
- Use for calibration of SCE
  - Know laser “true” tracks
  - But limited TPC coverage – see below



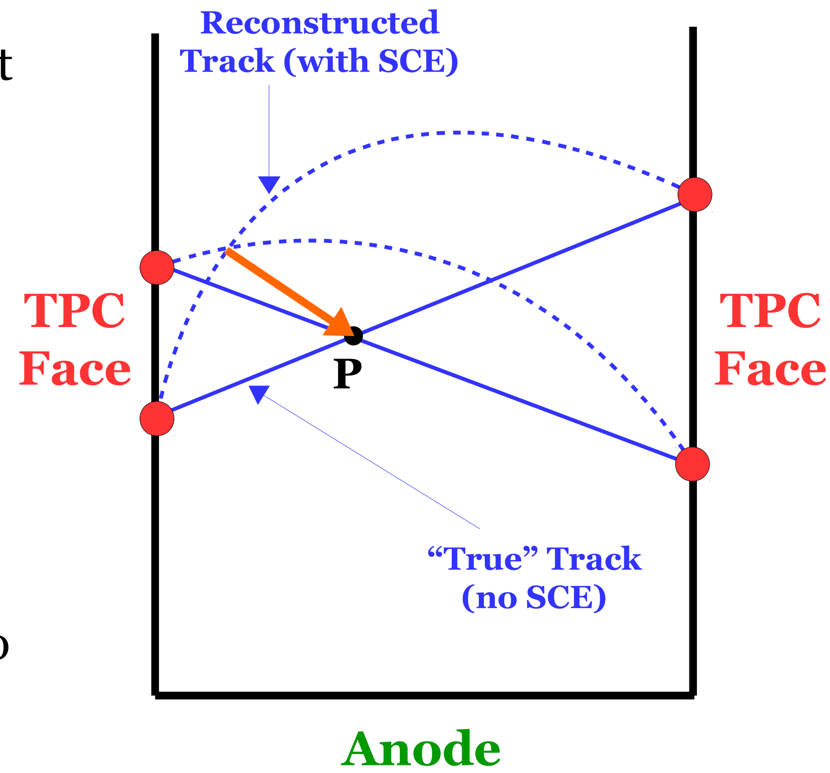




Need a Way to Fill in Gaps in Calibration Map!

Calibration Scheme

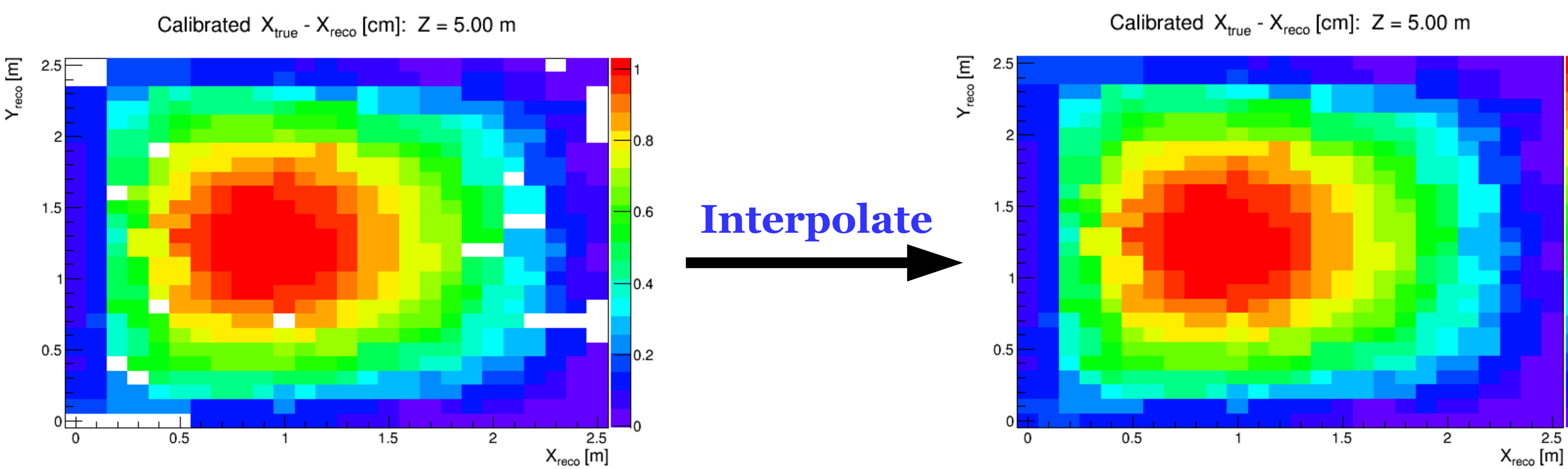
- Fill in displacement correction map gaps using **cosmic muons**
  - Approximately **10 cosmics** per event time window (4.8 ms)
- Correction from center of line connecting points of closest approach (separation **d**) between two tracks (before and after SCE)
  - Can use scheme for both laser and cosmic muon tracks
  - Get "true" muon track from PCA fit to already-calibrated points
  - Weight each contribution by $\mathbf{e^{-d/D}}$ (where **D** is tunable parameter)
  - Use only **high-momentum cosmics** to minimize MCS effects



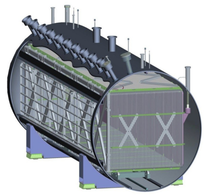
Update Correction to Point P

Interpolation, Notes

- Interpolate between gaps in correction map using 3D Delaunay triangulation (CGAL library)



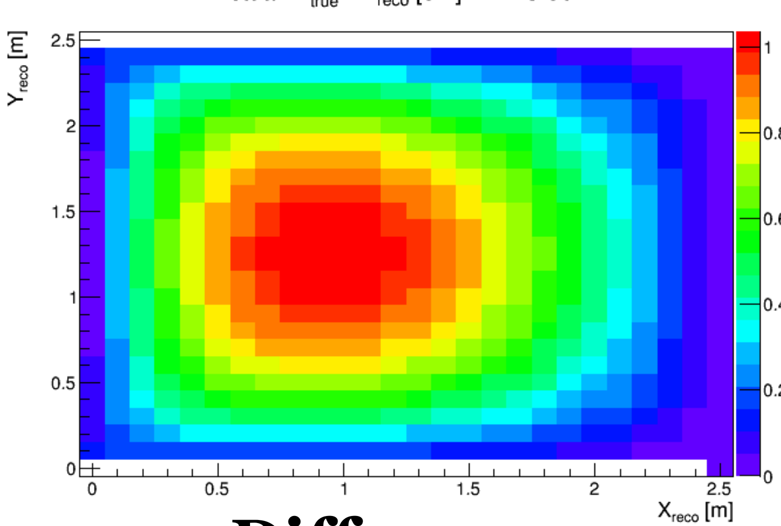
- Two version of results (use **10,000** high-momentum cosmics):
  - **<u>Ideal Case</u>**: assume perfect knowledge of cosmic muon "true" tracks
    - **Results shown today (others preliminary)**
  - **<u>Realistic Case</u>**: approximate cosmic muon "true" track from PCA fits using already-calibrated points (2+) from laser correction



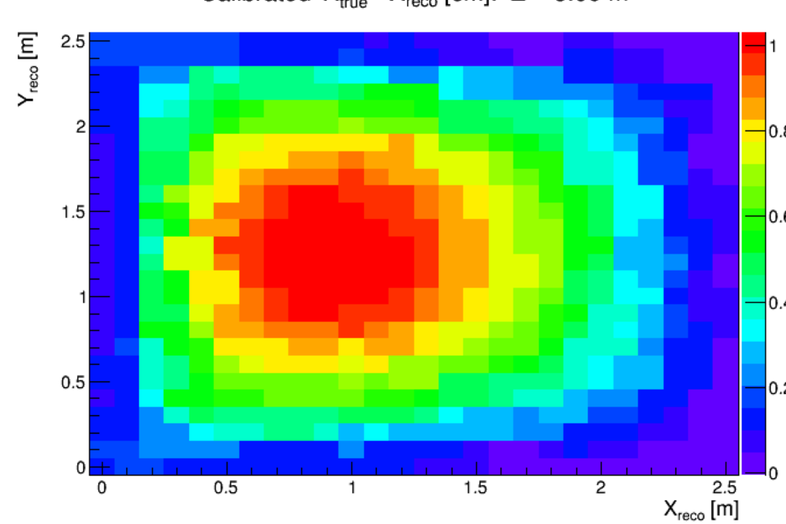
Results: ΔX (Z = 5.0 m)

Simulation

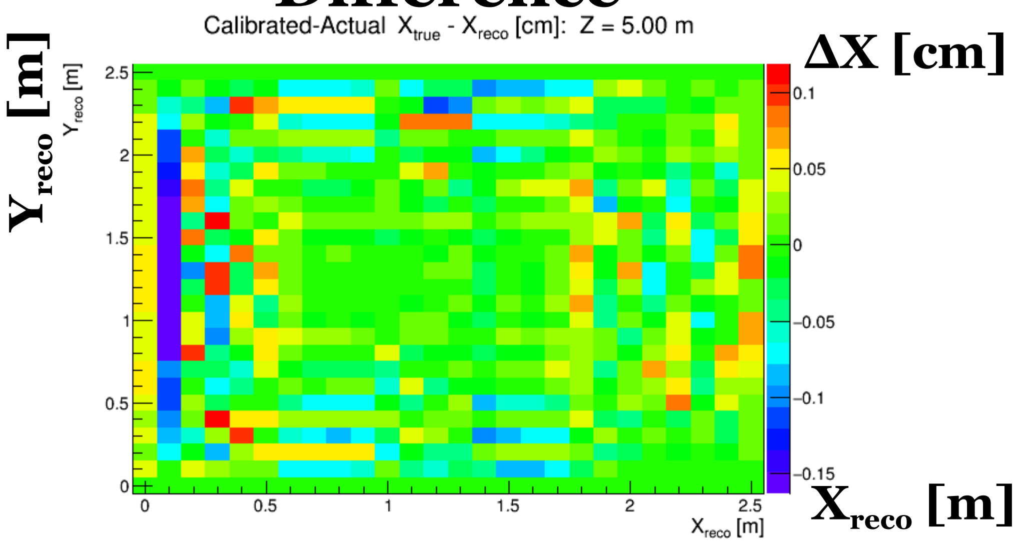
Ideal Case

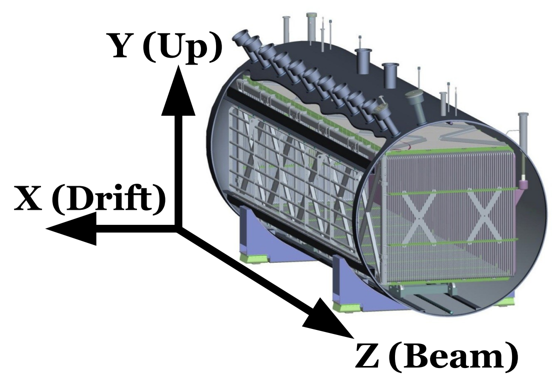


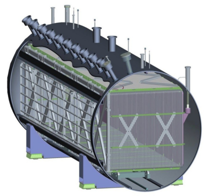
Calibration



Difference





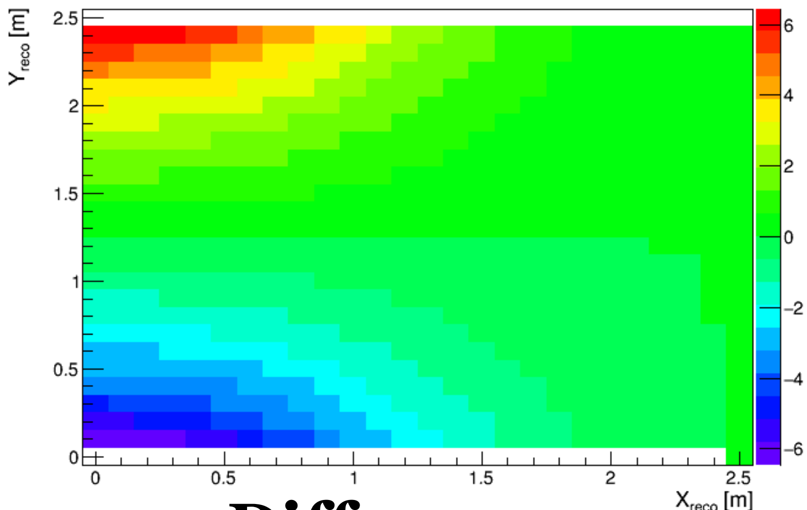


Results: ΔY (Z = 5.0 m)

Simulation

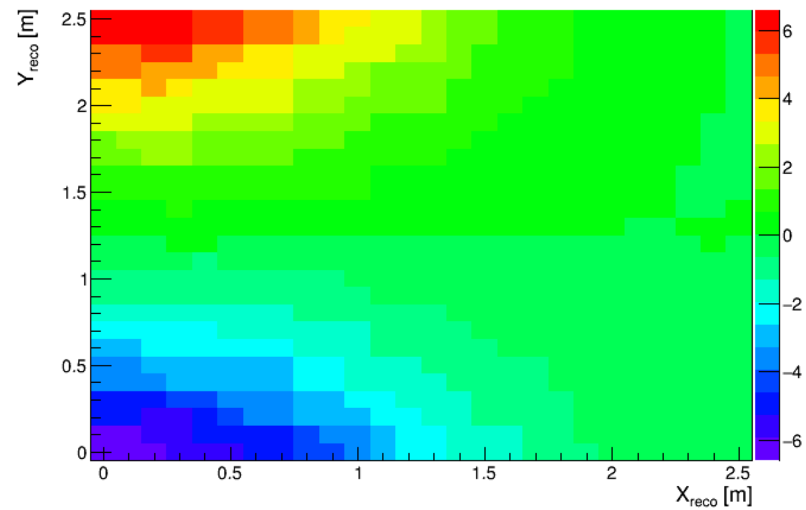
Ideal Case

Actual Y_{true} - Y_{reco} [cm]: Z = 5.00 m



Calibration

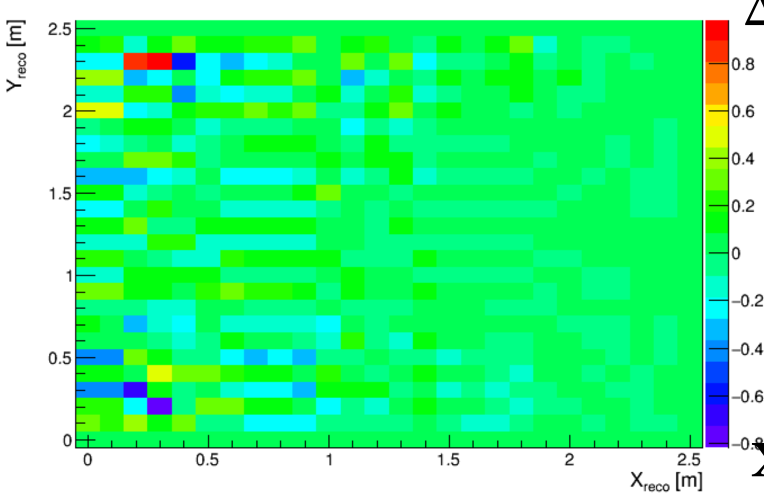
Calibrated Y_{true} - Y_{reco} [cm]: Z = 5.00 m



Difference

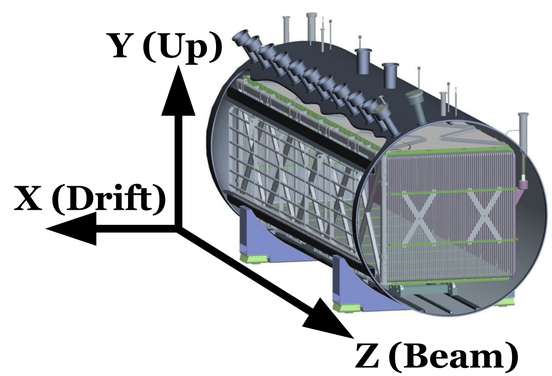
Calibrated-Actual Y_{true} - Y_{reco} [cm]: Z = 5.00 m

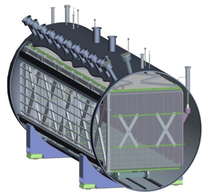
Y_{reco} [m]



ΔY [cm]

X_{reco} [m]



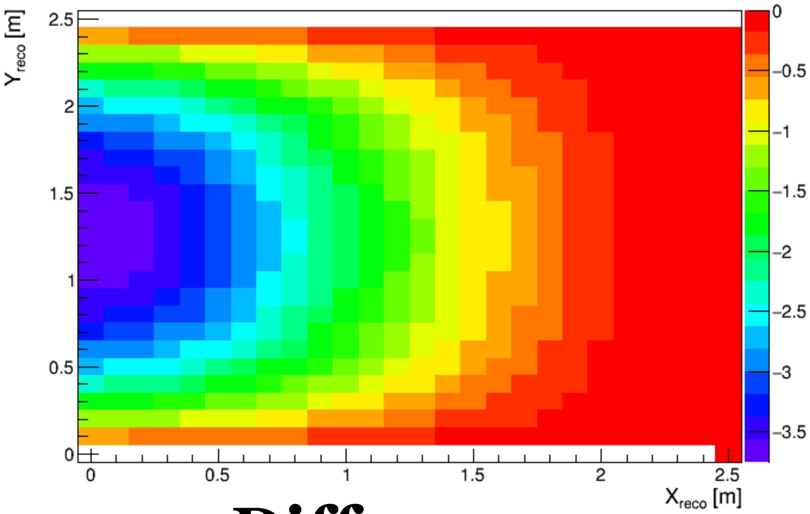


Results: ΔZ (Z = 0.3 m)

Simulation

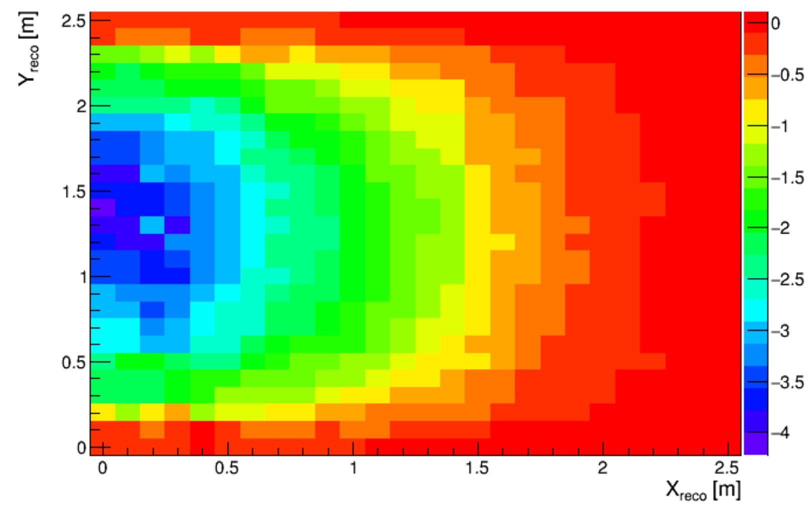
Ideal Case

Actual Z_{true} - Z_{reco} [cm]: Z = 0.30 m



Calibration

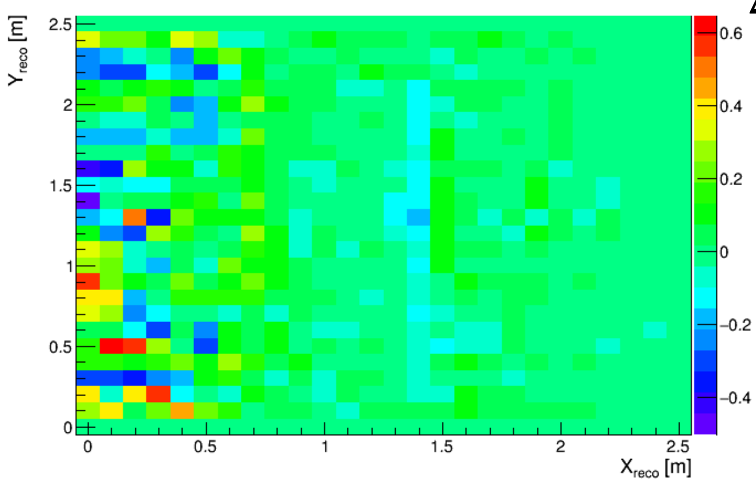
Calibrated Z_{true} - Z_{reco} [cm]: Z = 0.30 m



Difference

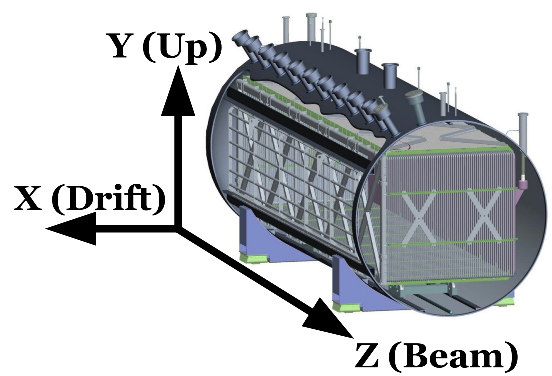
Calibrated-Actual Z_{true} - Z_{reco} [cm]: Z = 0.30 m

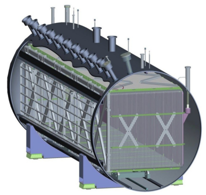
Y_{reco} [m]



ΔZ [cm]

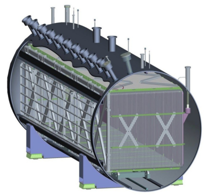
X_{reco} [m]



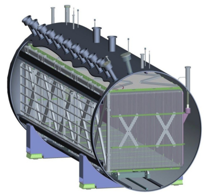


Summary

- First space charge effect calibration results for **MicroBooNE** look promising
  - Laser system alone provides ΔX and ΔY near center of TPC
  - Cosmic muons fill in entire TPC and improve ΔZ estimate
  - Studies of "Realistic Case" in progress
- Current studies make use of toy MC – commissioning at MicroBooNE ongoing and will have data for calibration very soon!
- **Many thanks to:**
  - **Christoph Rudolf von Rohr** (Uni. Bern graduate student)
  - **Matthias Luthi** (Uni. Bern graduate student)
  - **Navneet "Vik" Dhaliwal** (BNL undergraduate summer student)



BACKUP SLIDES



Advantages of LArTPC

Liquid Argon is an excellent choice for neutrino detectors:

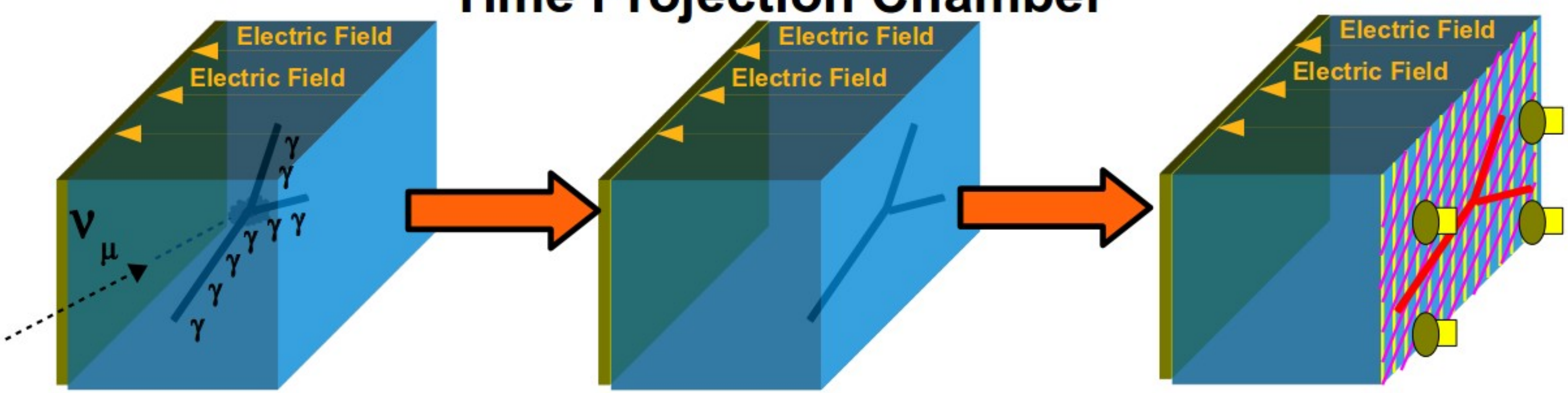
	He	Ne	Ar	Kr	Xe	Water
Boiling Point [K] @ 1atm	4.2	27.1	87.3	120.0	165.0	373
Density [g/cm³]	0.125	1.2	1.4	2.4	3.0	1
Radiation Length [cm]	755.2	24.0	14.0	4.9	2.8	36.1
dE/dx [MeV/cm]	0.24	1.4	2.1	3.0	3.8	1.9
Scintillation [γ /MeV]	19,000	30,000	40,000	25,000	42,000	
Scintillation λ [nm]	80	78	128	150	175	

Note: This table was first produced by my boss Mitch Soderberg and if he had patented it he would have 10's of dollars because it shows up in every LAr talk I've ever seen!

- → **Dense**
  40% more dense than water
- → **Abundant**
  1% of the atmosphere
- → **Ionizes easily**
  55,000 electrons / cm
- → **High electron lifetime**
  Greek name means "lazy"
- → **Produces copious scintillation light**
  Transparent to light produced

J. Asaadi

Time Projection Chamber

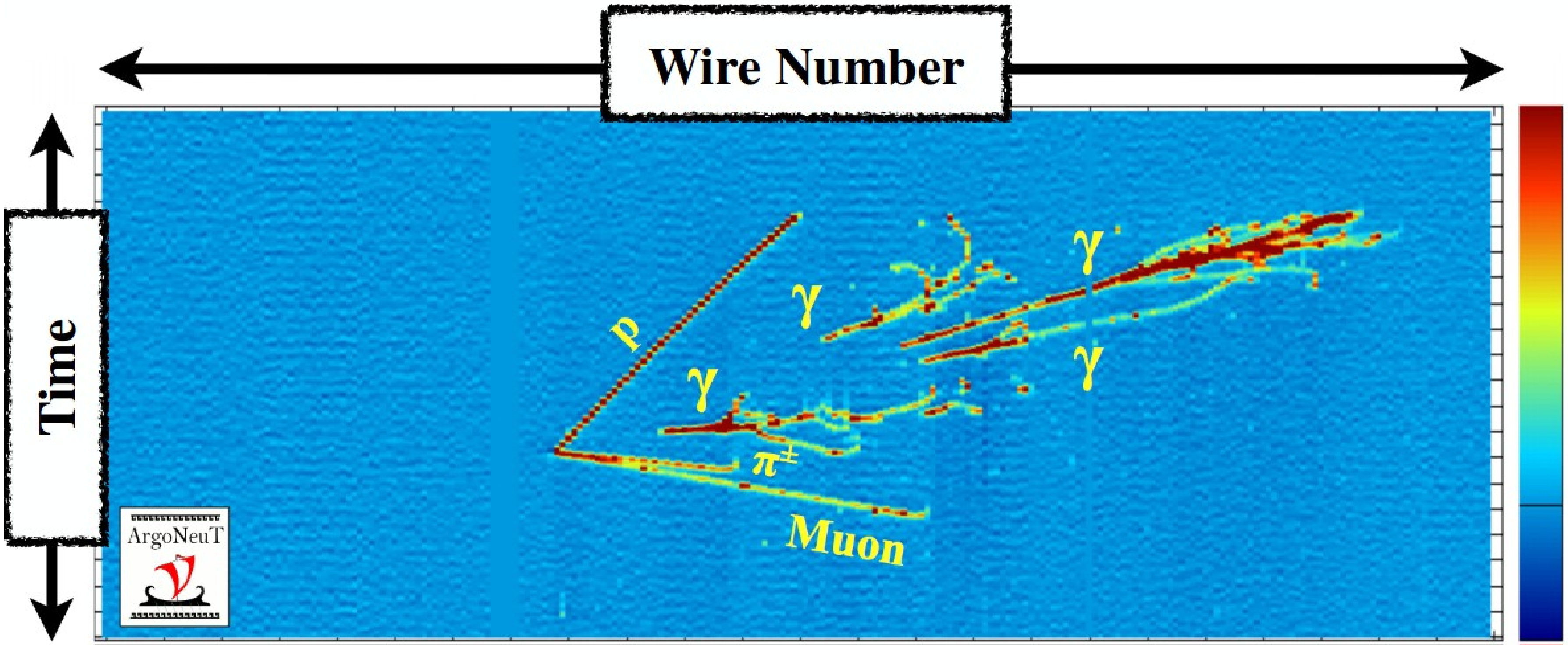


Neutrino interaction in LAr produces ionization and scintillation light

Drift the ionization charge in a uniform electric field

Read out charge and light produced using precision wires and PMT's

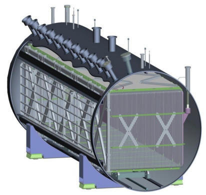
LarTPC Event Reconstruction



Example DIS event
(courtesy of ArgoNeuT collaboration)

Charge deposited

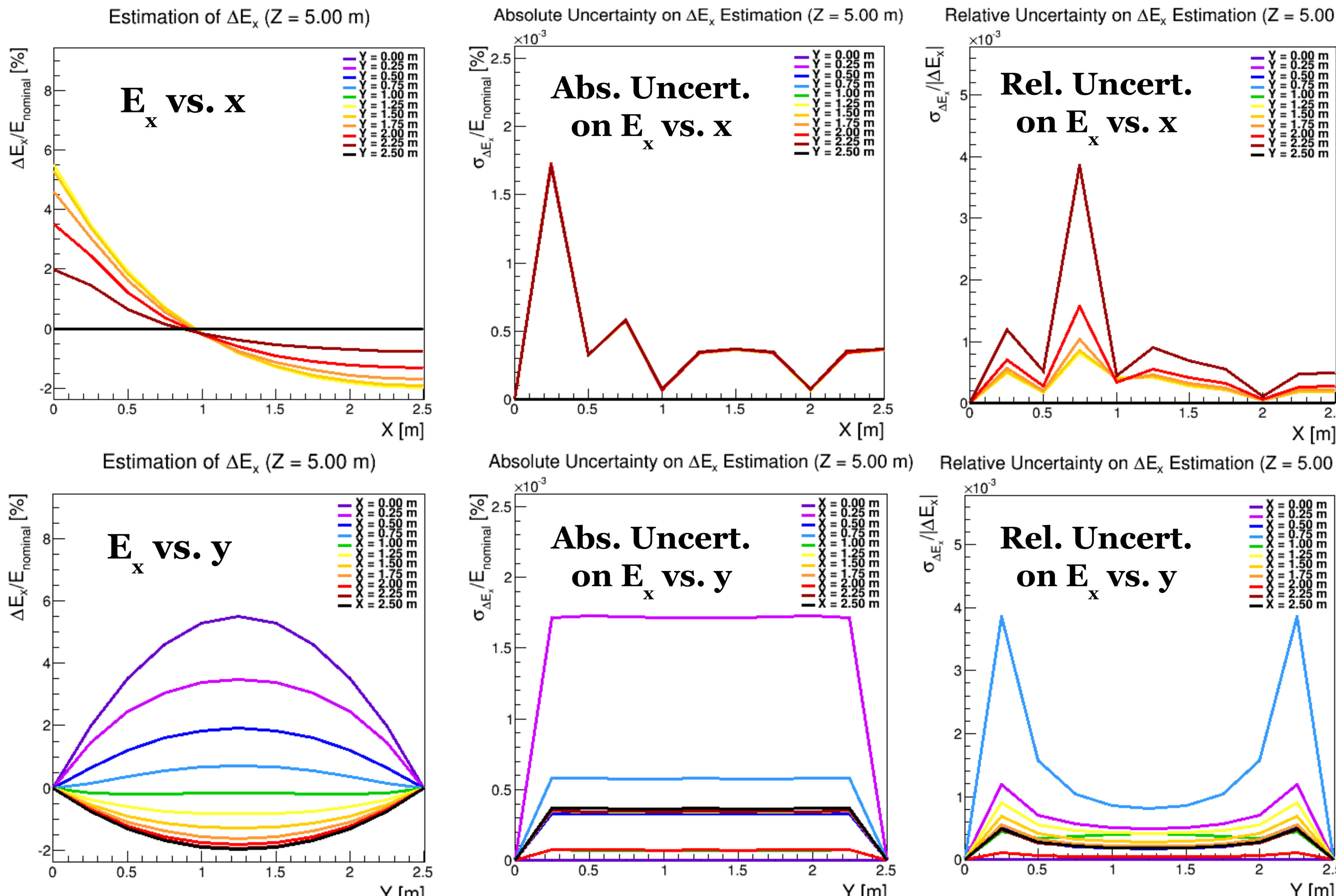
Combine different wire planes together to get 3D information



Simulation with SpaCE

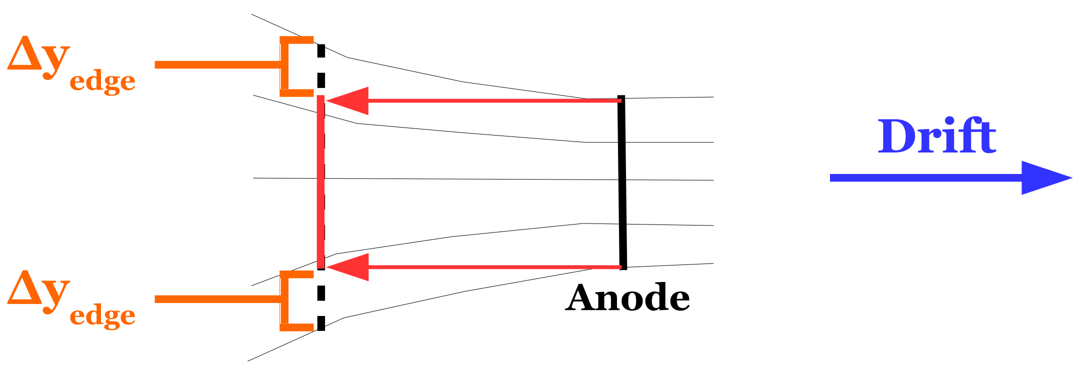
- **SpaCE**: **Spa**ce **C**harge **E**stimator – SCE simulation package written by M. Mooney
- Code written in C++ with ROOT/ALGLIB libraries
- Primary features:
  - Obtain E fields analytically (on 3D grid) via **Fourier series**
  - Use **interpolation** scheme (RBF – radial basis functions) to obtain E fields in between solution points on grid
  - Generate tracks in volume – line of uniformly-spaced points
  - Employ **ray-tracing** to "read out" reconstructed {x,y,z} point for each track point – RKF45 method
- Results presented here assume uniform space charge deposition without liquid argon flow
  - Can also use arbitrary charge distribution as input

E Field Calc. Uncertainty



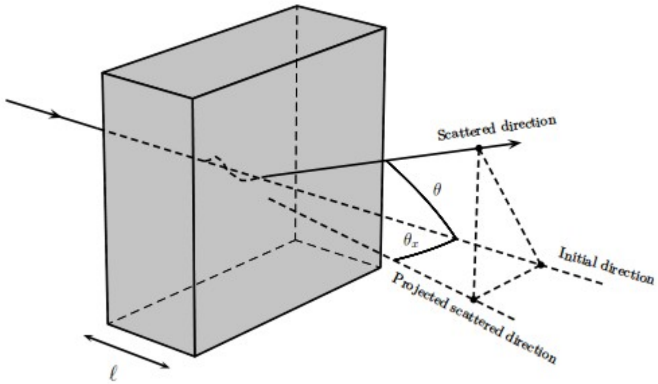
Smoking-gun Test for SCE

- Can use cosmic muon tracks for calibration
  - Possibly sample smaller time scales more relevant for a particular neutrino-crossing time slice
  - Minimally: data-driven cross-check against laser system calibration
- **Smoking-gun test**: see lateral charge displacement at track ends of non-contained cosmic muons → space charge effect!
  - No timing offset at transverse detector faces (no E_x distortions)
  - Most obvious feature of space charge effect



Using MCS to Measure p_{track}

Small angle deflections are governed by the so-called modified Highland formula



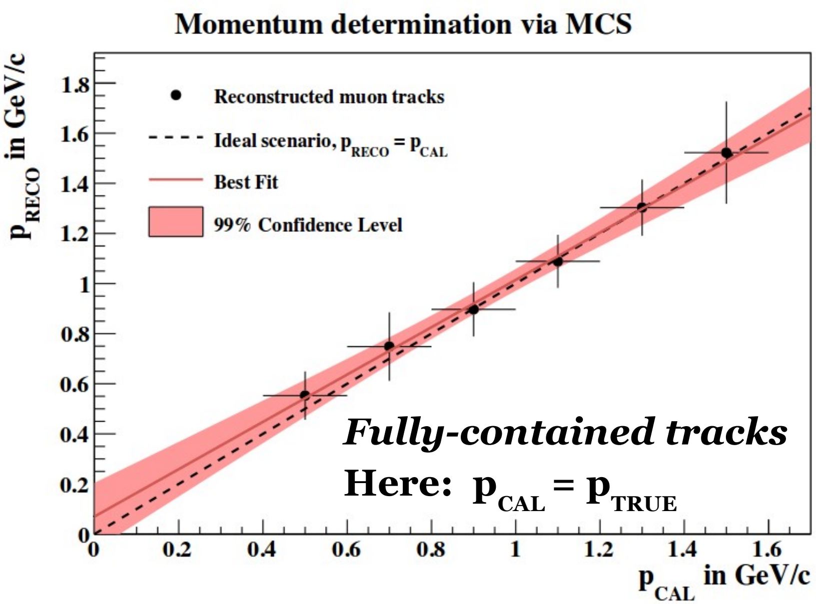
$$\theta_0 = \frac{13.6}{p\beta c}\sqrt{\frac{\ell}{X_0}}\left[1 + 0.0038\, \ell n\left(\frac{\ell}{X_0}\right)\right]$$

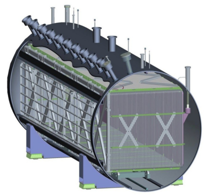
θ_0 : RMS of the $\Delta\theta$ distribution (mrad)
p : particle momentum (GeV/c)
\ell : material thickness
X_0 : radiation length

<u>Idea</u>: RMS of $\Delta\theta$ distribution → p_{track} ("p_{RECO}")

L. Kalousis

- One idea: use angular deflections of track due to Multiple Coulomb Scattering (MCS) in order to find $\mathbf{p_{track}}$
- Need to see how SCE impacts this measurement!





Calibration Scheme: SCT

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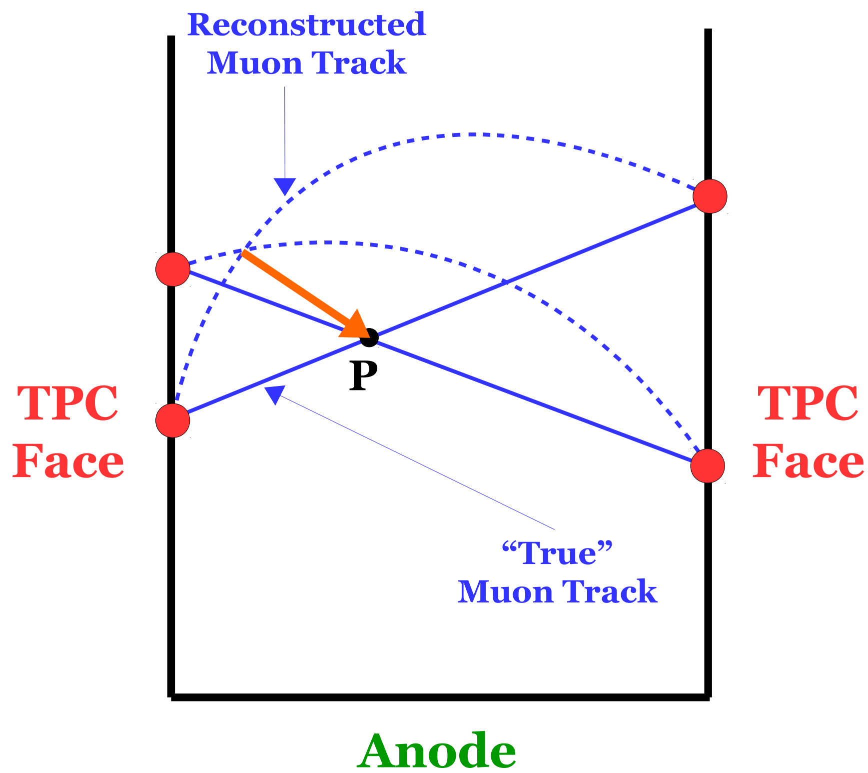
- Fill in displacement correction maps (in between where laser system can reach) using **cosmic muons**
  - Approximately **10 cosmics** per event time window (4.8 ms)
- Algorithm: **Space Charge Tomography (SCT)**
- Step definitions:
  - Use (near) laser crossings – **"X"**
  - Update cosmic muon "truth track" using fit (PCA) to corrected track points that pass through previously-calibrated regions – **"T"**
  - Use (near) crossings of single laser track and single cosmic track – **"L"**
  - Use (near) crossings of two cosmic muons – **"μ"**
- **Progression of SCT steps**: **X → T → L → T → μ → T → L → ...**
  - Obtain cosmic muon t_o from PMT system
  - With high enough statistics, **multiple-scattering averaged out** (also use high-momentum tracks to minimize effect)

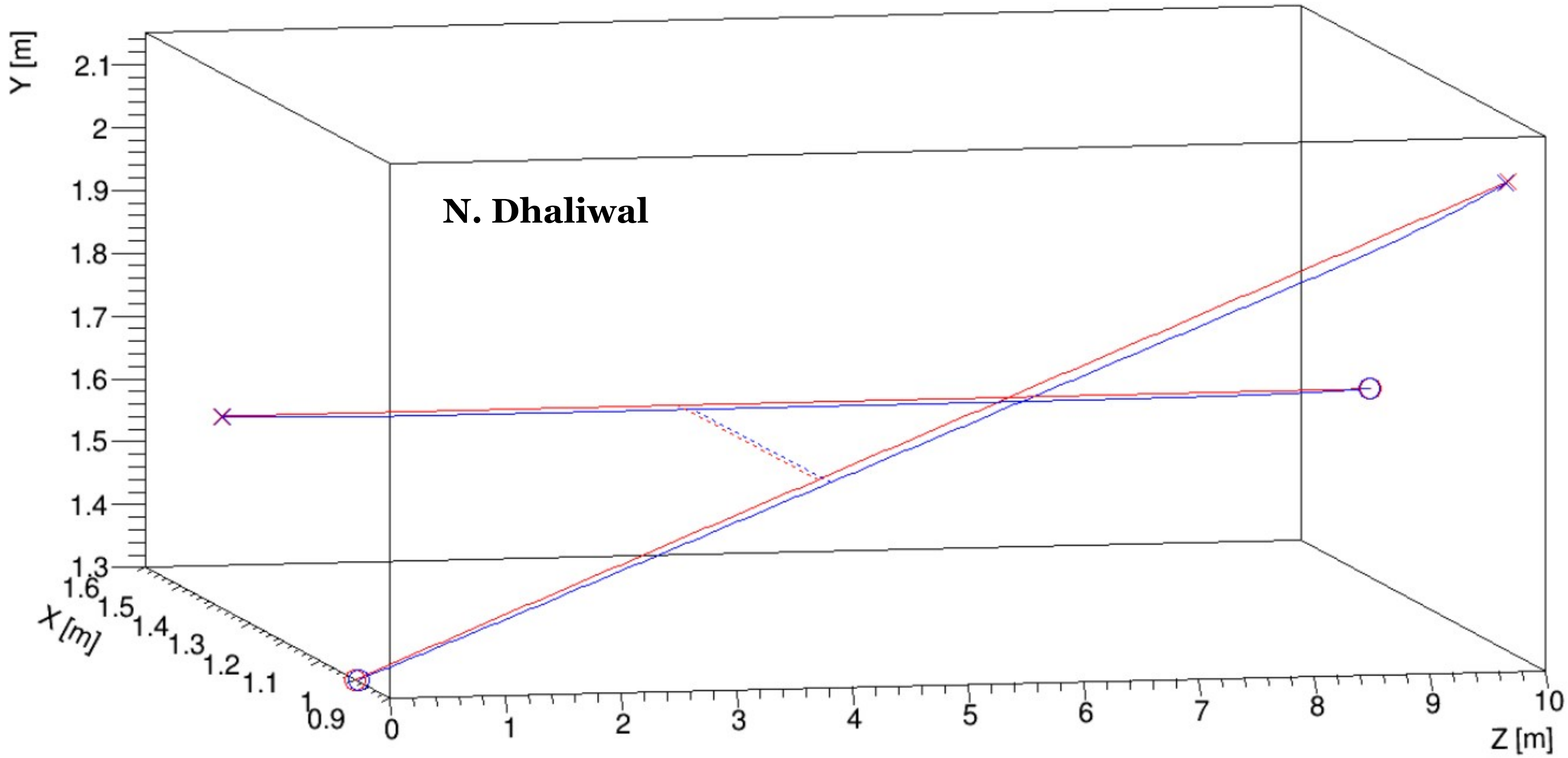
SCT "μ" Step

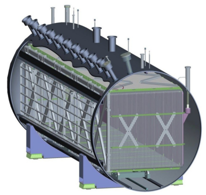
- Calibration scheme details (using "**μ**" step as example):
  - Correction from center of line connecting points of closest approach (separation **d**) between two tracks (before and after SCE)
  - Get "true" muon track from **"T"** step (see previous slide)
  - Weight each contribution by factor $\mathbf{e^{-d/D}}$ (D is tunable parameter)
  - Use only **high-momentum cosmics** to minimize MCS effects



Update Correction to Point P

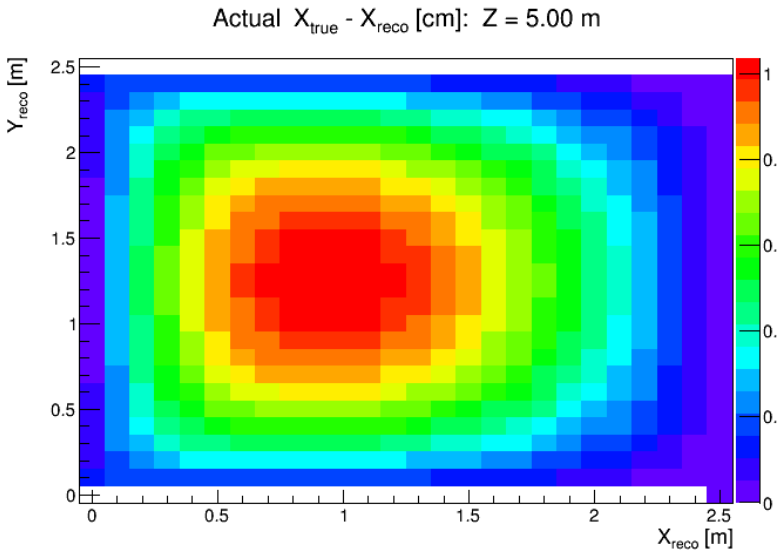
Distance of Closest Approach



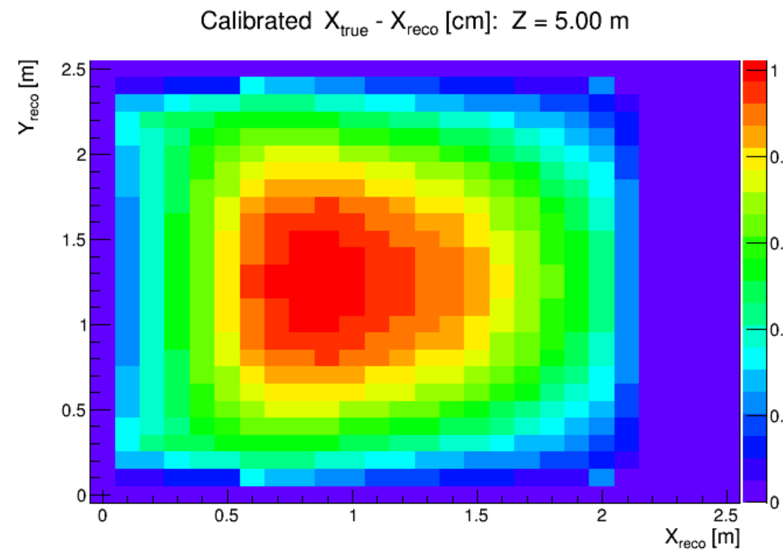


Laser-Only Results: ΔX (Z = 5.0 m)

Simulation

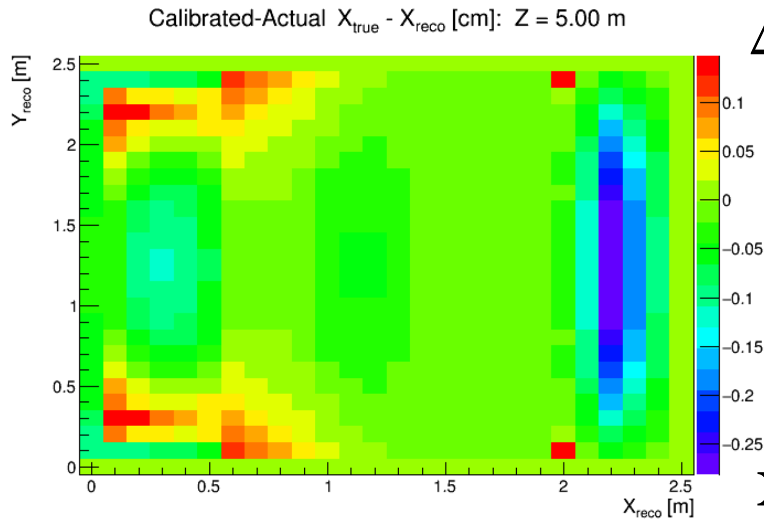


Calibration



Difference

Y_{reco} [m]



ΔX [cm]

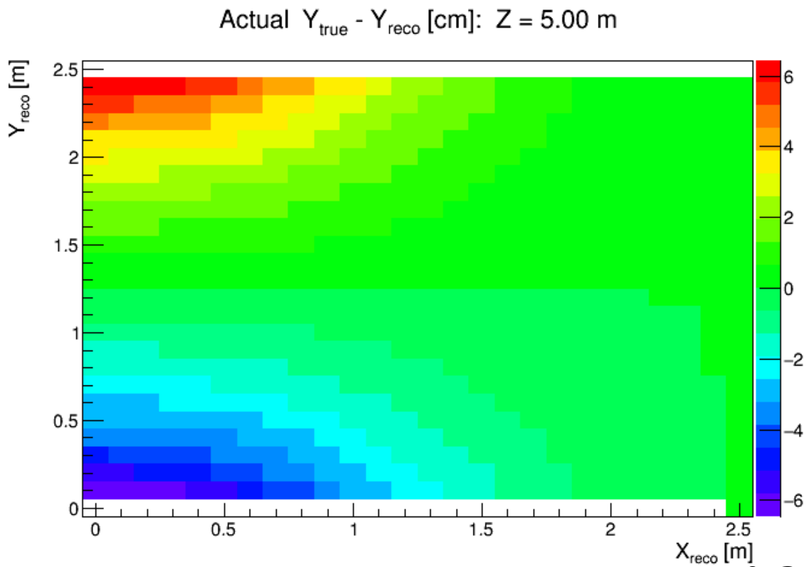
X_{reco} [m]

Algorithm:

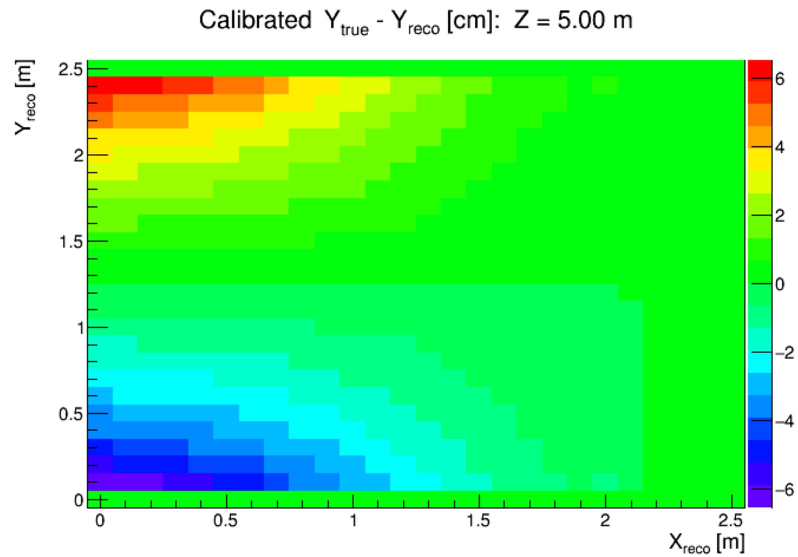
C. Rudolf von Rohr

Laser-Only Results: ΔY (Z = 5.0 m)

Simulation

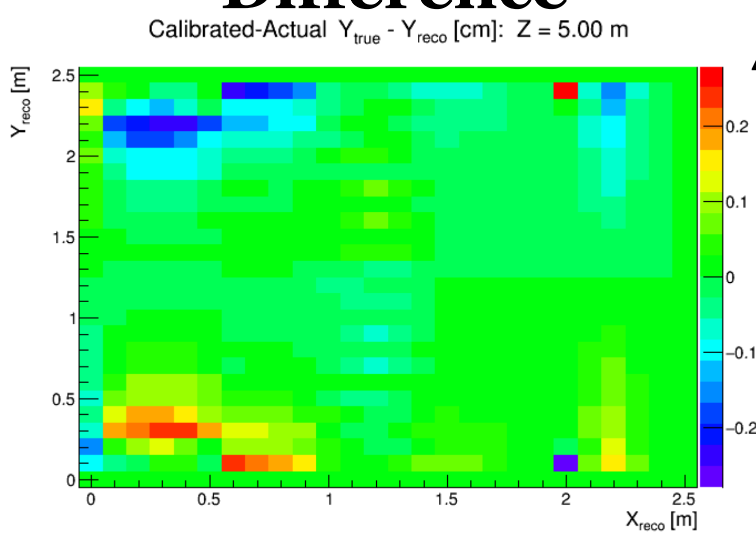


Calibration



Difference

Y_{reco} [m]



ΔY [cm]

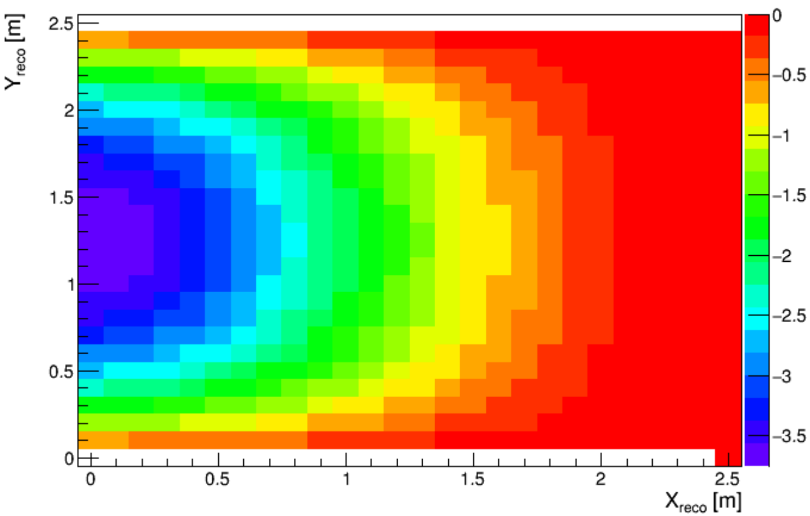
X_{reco} [m]

Algorithm:

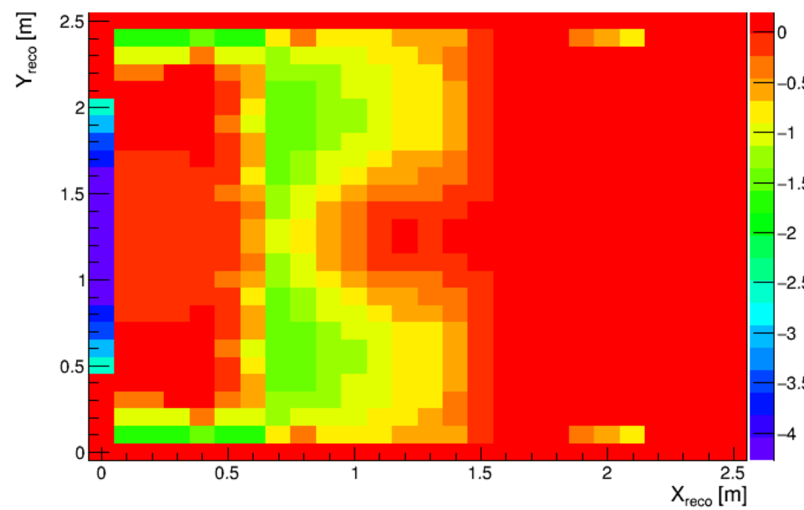
C. Rudolf von Rohr

Laser-Only Results: ΔZ (Z = 0.3 m)

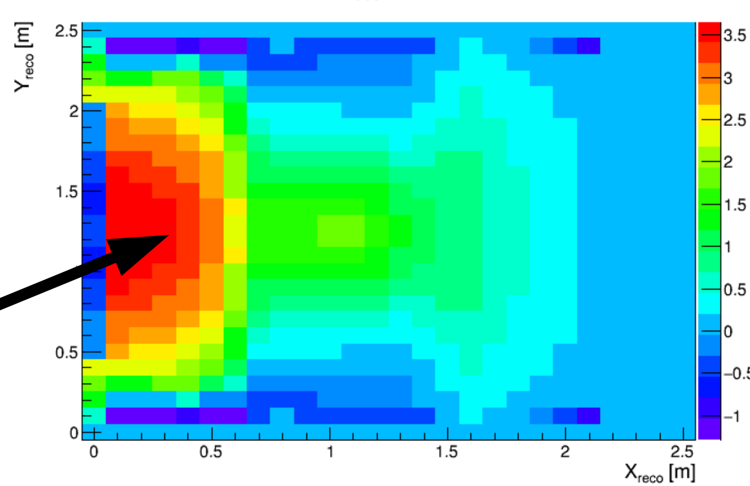
Simulation



Calibration



Difference



Y_{reco} [m]

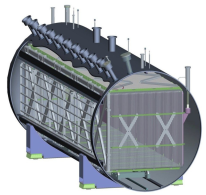
ΔZ [cm]

X_{reco} [m]

Need Aid from Cosmics

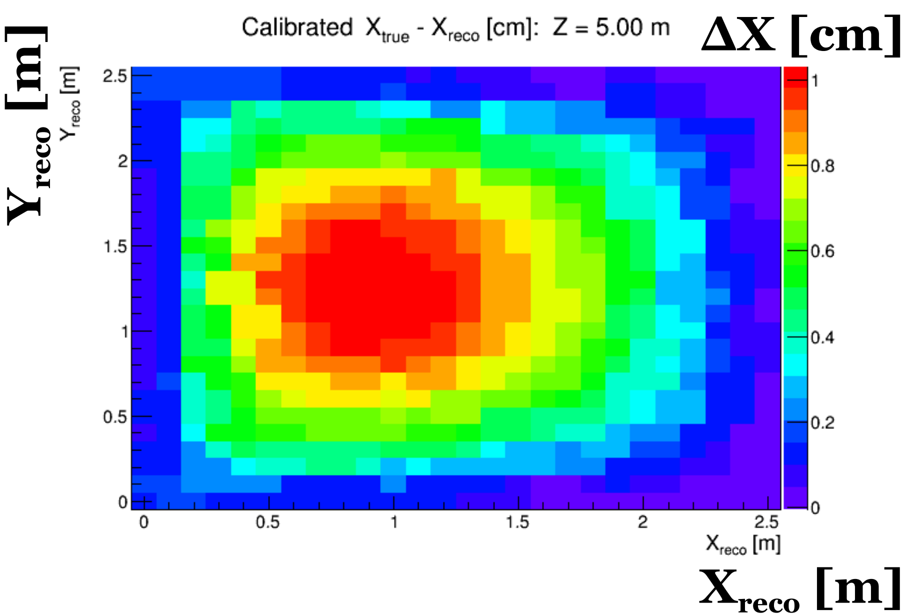
Algorithm:

C. Rudolf von Rohr

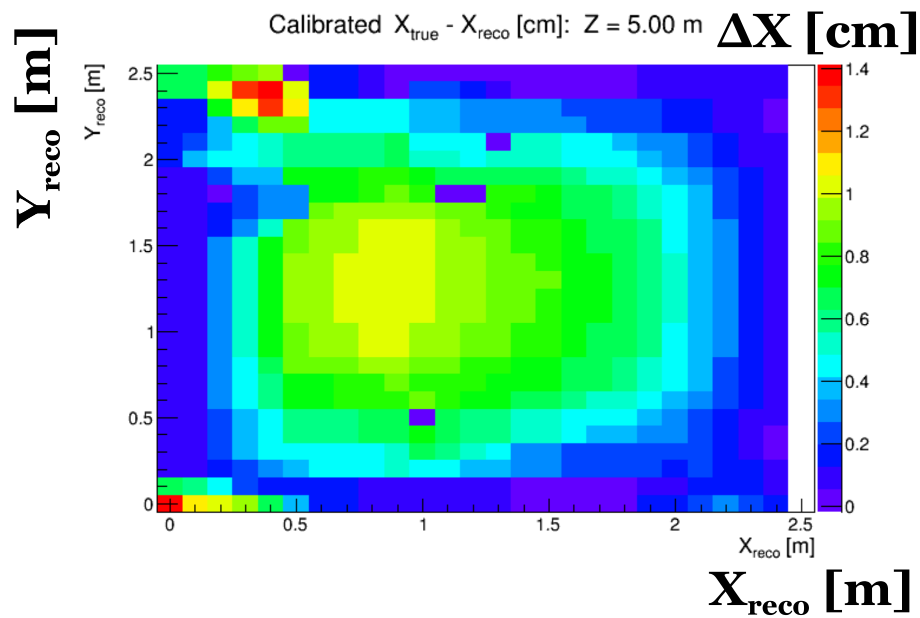


Ideal Case vs. Realistic Case

Ideal Case



Realistic Case



- Using ΔX in central Z slice (Z = 5.0 m) as an example **(preliminary)**
- General shape/magnitude of correction obtained in realistic case, but some discrepancies in corners
- Likely need more tracks (only used **1,000 cosmics** here for realistic case) and to throw out low-weight contributions from track pairs